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Changes in air quality related to the control of coronavirus in China: Implications for traffic and industrial emissions

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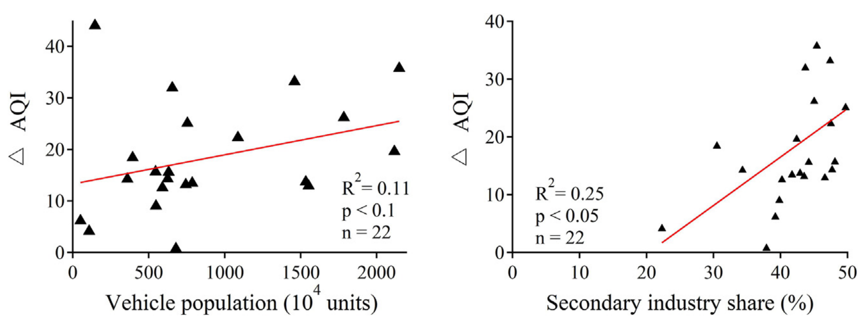
HIGHLIGHTS

- The overall air quality was improved during the control of Covid-19.
- The improvement was caused by reduced emissions from transportation and industry.
- It is necessary to strengthen emissions from the residential sector.

GRAPHICAL ABSTRACT



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ABSTRACT

Measures taken to control the disease (Covid-19) caused by the novel coronavirus dramatically reduced the number of vehicles on the road and diminished factory production. For this study, changes in the air quality index (AQI) and the concentrations of six air pollutants ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, and O_3) were evaluated during the Covid-19 control period in northern China. Overall, the air quality improved, most likely due to reduced emissions from the transportation and secondary industrial sectors. Specifically, the transportation sector was linked to the NO_2 emission reductions, while lower emissions from secondary industries were the major cause for the reductions of $PM_{2.5}$ and CO. The reduction in SO_2 concentrations was only linked to the industrial sector. However, the reductions in emissions did not fully eliminate air pollution, and O_3 actually increased, possibly because lower fine particle loadings led to less scavenging of HO_2 and as a result greater O_3 production. These results also highlight need to control emissions from the residential sector.

1. Introduction

In December 2019, a disease that was eventually linked to a beta coronavirus and named Covid-19 was reported in Wuhan, China (Zhu et al., 2020). In the weeks that followed, measures were taken to reduce large gatherings to control the spread of the disease (China State

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Council, 2020). For example, the Spring Festival holiday was extended beyond February 10, and during that time only essential enterprises involving people's immediate needs (such as health care, or providing food), were allowed to operate. In addition, the opening of schools after the holiday was postponed.

These measures led to a dramatically reduced number of vehicles on the road and a near total reduction in factory production (MEP, 2020; Wang et al., 2020). Pollution emissions from the transportation and industrial sectors were expected to decrease, and the following questions can be asked: Did the air quality improve during the control of Covid-19? If so, how was the improvement related to the reduced emissions from these two sectors? Also, what was the major cause for the improvements in air quality and which atmospheric species were most affected? Answering these questions is a way to evaluate the influences of traffic and industrial emissions on air quality during winter in China. The results of the evaluation can then be used to make recommendations regarding air pollution control during winter in China.

In this study, changes in the air quality index (AQI) and the concentrations of six air pollutants ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, and O_3) were evaluated, and the causes for these changes during the control period for Covid-19 were investigated. Correlation analyses were then used to analyze the relationships between socioeconomic factors (i.e., motor vehicle usage, percentage of secondary industries, and industrial emissions) and air quality. Finally, suggestions are given for air pollution control in China during winter.

2. Methods

2.1. Study area and period

A total of 366 urban areas in China's mainland were selected for study. These cities are widely distributed over China with the greatest coverage in eastern-southeastern parts of the country (Fig. 1). Taken together, the sites can be considered representative of the overall air quality in China (Kuerban et al., 2019; Zhao et al., 2019).

The overall strategy for the study was to compare the concentrations of selected pollutants before and after the Covid-19 control measures were put in place. The period prior to the controls was from 1 to the 23 January 2020, while the Covid-19 control period was from 24 January to 9 February 2020. During the control period, a series of measures was undertaken to reduce gatherings of people (China State Council, 2020). Specifically, all non-essential factories were shut down, and schools were closed as were all entertainment venues and restaurants. A dramatic reduction in road traffic was observed during the control period. For example, the flow of commercial trucks and buses in the Beijing-Tianjin-Hebei region and its surrounding areas decreased by 77% and 39%, respectively, during the control period (MEP, 2020).

2.2. Data sources

The real-time monitoring data for AQI, $PM_{2.5}$, PM_{10}, SO_2, NO_2, O_3, and CO in the 366 urban areas were obtained from China's National Environmental Monitoring Center. The data had a time resolution of 1 h (http://

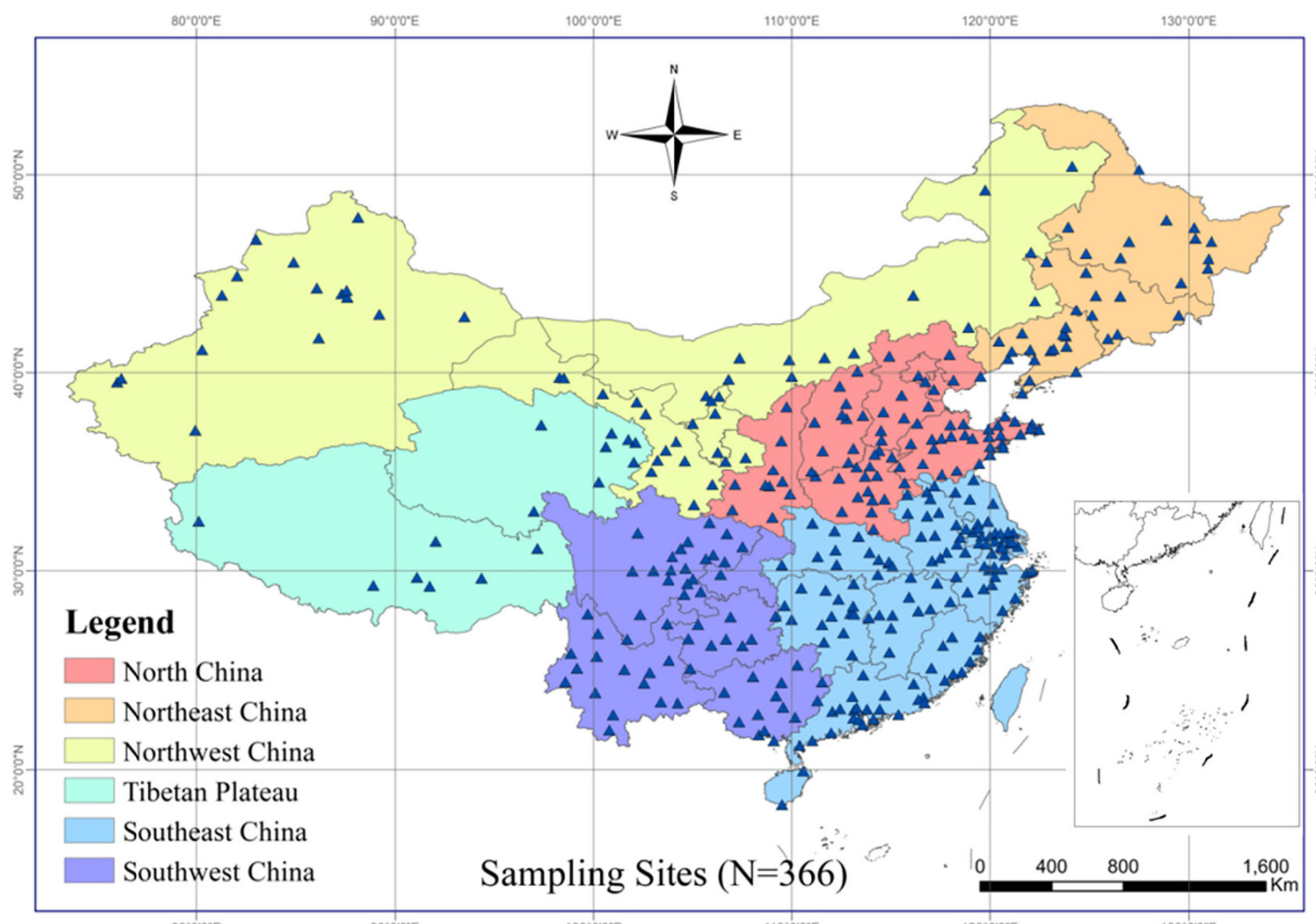

Fig. 1. Geographical locations of 366 urban areas included in the study.

www.cnemc.cn). Previous studies have shown that data from China's National Environmental Monitoring Center are statistically reliable (Kuerban et al., 2019; Zhao et al., 2019). The AQI monitoring values calculated from the six priority pollutants (Bai et al., 2019) and the data for the individual pollutants themselves were averaged for the periods prior to and during the Covid-19 controls.

The geographical distributions of secondary industries (which convert raw materials produced by primary industries into goods and products) and industrial SO_2 and NO_x emissions were obtained from the 2018 China City Statistical Yearbook. The numbers of motor vehicles in operation were obtained from the China Statistic Yearbook. Notably, the socioeconomic data from seven provinces (Tianjin, Sichuan, Jilin, Heilongjiang, Gansu, Xinjiang, and Qinghai) where the holiday was not extended to February 10, were not used in this study (Table S1).

3. Results and discussion

3.1. Air quality during the control of Covid-19

Significant differences ($p < 0.01$) were found in the AQI and the concentrations of six air pollutants ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2, and O_3) of 366 urban areas before and during the control of Covid-19, suggesting the air quality changed during the control period. The AQI averaged over all stations decreased by 20%, from 89.6 before the control period for Covid-19 to 71.6 during the controls (Fig. 2), demonstrating an overall improvement in air quality from the control measures. A total of 322 of the 366 cities studied experienced a decline in the AQI. The highest AQI reductions occurred in the Ningxia, Shandong, and Henan Provinces (Fig. S1), which normally have high numbers of vehicles in use (Shandong and Henan) (Fig. S2a) and many secondary industries in operation (Ningxia, Shandong, and Henan) (Fig. S2b). The lowest AQI reductions occurred in the Yunnan, Guizhou, and Hainan Provinces (Fig. S1), where motor vehicle usage and secondary industries are relatively low (Fig. S2). Therefore, the improvement of air quality apparently was related to the number of motor vehicles in use and the percentages of secondary industries in each province. The AQI in 366 urban areas had the highest correlation coefficient (r^2 of 0.99) with the $PM_{2.5}$ before and during the control of Covid-19, which reflects the fact that fine particles were the major air pollutant throughout the study.

The concentrations of the $PM_{2.5}$, PM_{10}, SO_2, NO_2, and CO, but not O_3, decreased during the Covid-19 control period (Fig. S3) compared with those before the controls were put in place. The concentration of $PM_{2.5}$, decreased from 65.0 $\mu g\ m^{-3}$ to 51.4 $\mu g\ m^{-3}$ (Fig. S3), and 315 of the 366 cities experienced a decrease in $PM_{2.5}$. The regions with the highest and lowest reductions in $PM_{2.5}$ concentrations were the same

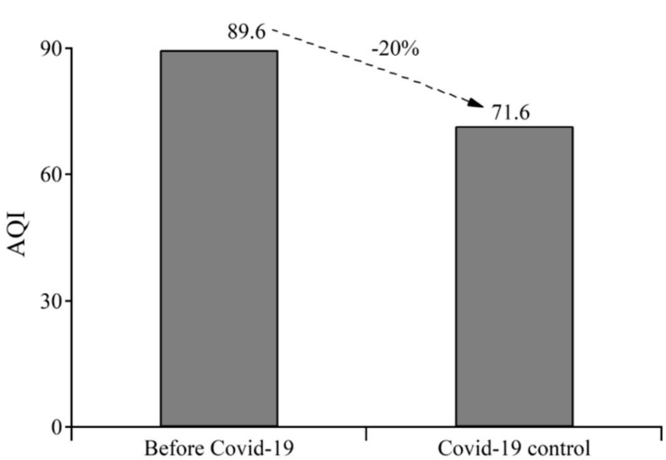

Fig. 2. Comparison of air quality indices (AQI) before and during the control of Covid-19.

as those for the AQI (Figs. S1, S4), again, because fine particles were most often the major air pollutant.

After the controls were implemented, the concentrations of CO, SO_2, and NO_2 decreased by 0.23 mg m^{-3}, 2.2 $\mu g\ m^{-3}$, and 19.4 $\mu g\ m^{-3}$, respectively (Fig. S3). A total of 331 (309, 366) of the 366 cities studied experienced reductions in CO (SO_2, NO_2). The highest reductions of CO and NO_2 occurred in the Shandong and Henan Provinces (Figs. 3, S5) where there are large numbers of motor vehicles and many secondary industries (Fig. S2). This suggests that the reduced emissions from the transportation and industrial sectors were what caused the concentrations of these two gases to decrease. The largest decreases in SO_2 were found in Shanxi and Jiangxi Provinces (Fig. 4), which have low numbers of vehicles but many secondary industries (Fig. S2). This indicates that the reduced SO_2 concentration was probably caused by the lower emissions from secondary industries during the control period.

The amplitude of the concentration variation (ACV) was calculated using the equation, $ACV = (y - x) / x \times 100\%$, where x and y are the mass concentrations of a substance of interest before and during the control period for Covid-19, respectively. The air pollutant that showed the largest decrease with the Covid-19 controls was NO_2 ($ACV = -54\%$) (Fig. S3) while SO_2, showed the smallest decline ($ACV = -16\%$). The SO_2/NO_2 ratio is an indicator of the relative contributions of air pollutants from stationary versus mobile sources (Aneja et al., 2001), and higher values occur when there are greater influences from stationary sources. The SO_2/NO_2 ratio averaged over the two sets of samples increased from 0.39 to 0.70 after the controls were in place (Fig. S6), suggesting an increase in the relative importance of stationary sources (Song et al., 2017). The AVCs for $PM_{2.5}$ and PM_{10} were -21% and -27%, respectively (Fig. S3), and the $PM_{2.5}/PM_{10}$ ratio increased from 0.76 to 0.82 (Fig. S6); these are signs of either decreased impacts from dust sources or enhanced secondary aerosol formation during the Covid-19 control period (Song et al., 2017; Zhao et al., 2018).

3.2. Factors driving the improvements in air quality

Significantly positive relationships were found between the numbers of motor vehicles and the reduced AQIs ($R^2 = 0.11$, $p < 0.1$; Fig. 5) and between the percentages of secondary industries and the change in AQIs ($R^2 = 0.25$, $p < 0.05$; Fig. 5). With the people largely confined to their homes, the provinces with higher numbers of vehicles should have had greater reductions in vehicle emissions during the control period, and the same should have been true for the secondary industries. The decreases in AQIs were more strongly correlated with the percentages of secondary industries than with motor vehicle numbers (Fig. 5), suggesting that the changes in industrial emissions were more responsible for the improvements air quality, especially fine particles, than motor vehicle usage.

The decreased $PM_{2.5}$ concentrations were positively correlated with motor vehicle numbers ($R^2 = 0.11$, $p < 0.1$; Fig. 6) and percentages of secondary industries ($R^2 = 0.28$, $p < 0.05$; Fig. 6). Therefore, the reduction in the $PM_{2.5}$ is best explained by lower emissions from the transportation and industrial sector. The reduced NO_2 concentrations were positively correlated with both vehicle numbers ($R^2 = 0.44$, $p < 0.001$; Fig. 6) and industrial NO_x emissions ($R^2 = 0.36$, $p < 0.01$; Fig. 6), indicating that decreased emissions from both the transportation and industrial sectors led to improvements in NO_2. As the reduced NO_2 concentrations were more strongly correlated with vehicle population than with the industrial NO_x emissions, transportation probably was more responsible for the decrease in NO_2 concentrations. The SO_2 concentrations showed a significant positive relationship with industrial SO_2 emissions ($R^2 = 0.16$, $p < 0.1$; Fig. 6) but not with motor vehicle numbers. Therefore, the reduced SO_2 concentrations were only linked to the industrial sector. The CO concentrations showed a significant positive correlation with both the vehicle numbers ($R^2 = 0.17$, $p < 0.05$; Fig. 6) and percentages of secondary industries ($R^2 = 0.29$, $p < 0.01$;

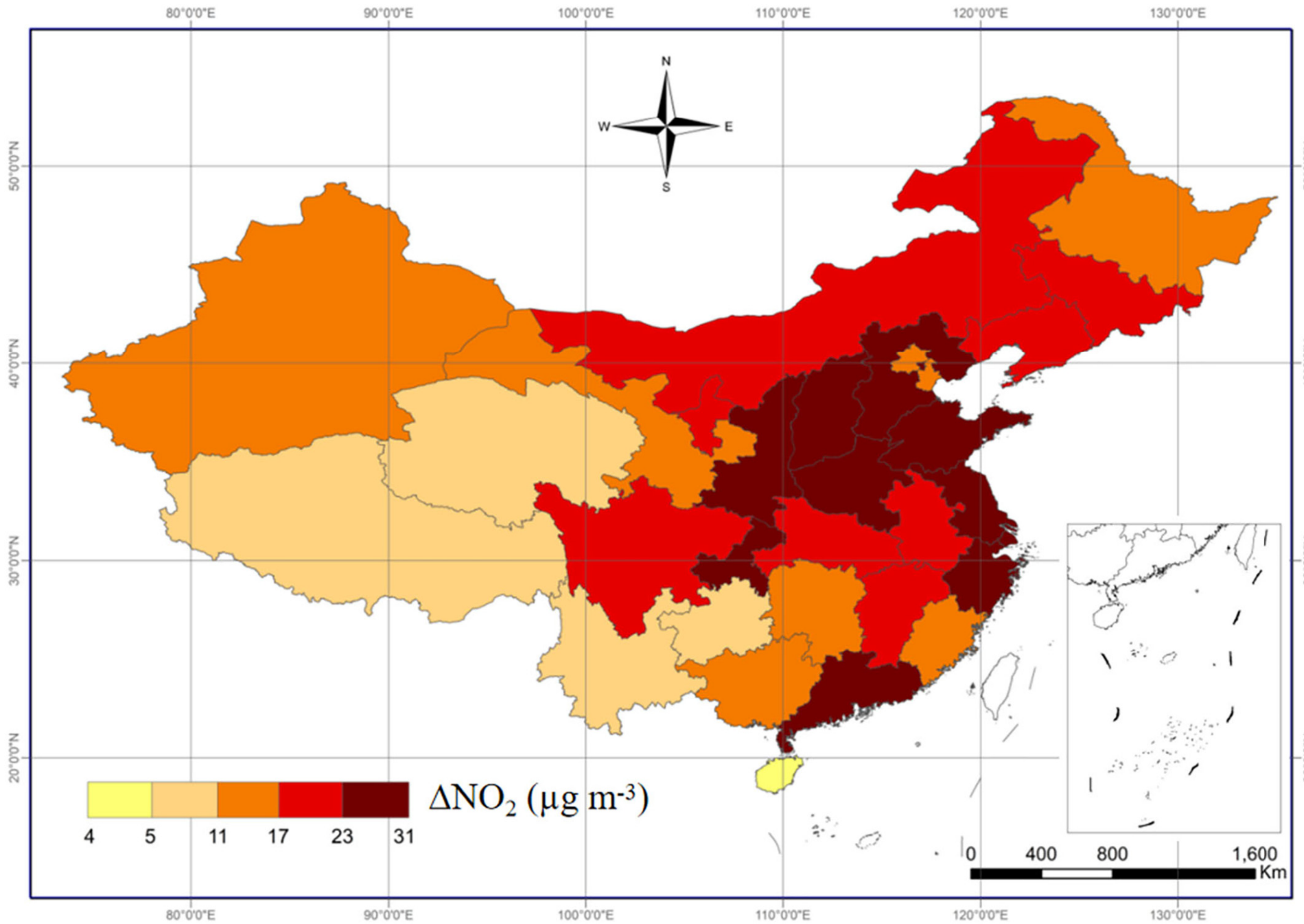

Fig. 3. Change in NO_2 mass concentrations (ΔNO_2) between the pre-control and Covid-19 control period. ΔNO_2 refers to the average NO_2 mass concentrations before the control of Covid-19 in each province minus the average NO_2 mass concentrations during the control period.

Fig. 6), but the stronger correlation with the latter (Fig. 6) suggests a reduction in industrial emissions was more responsible for the decrease.

3.3. Policy implications

3.3.1. Reducing air pollution

The air quality improved during the control period for Covid-19, and that apparently was mainly caused by reductions in emissions from the transportation and industrial sectors. The transportation sector was the major factor for the reduction of NO_2 mass concentrations, indicating the control measures greatly reduced the pollution emissions caused by the movement of people. As a major pollutant emitted from the coal heating in winter (Kuerban et al., 2019), the mass concentration of SO_2 decreased the least, suggesting the emissions from coal heating activities were probably little affected by the control measures.

Although the air quality improved, the average AQIs in 84 of the 169 cities in northern China were >100 after the controls were implemented, suggesting that the air pollutants in many cities were still at harmful levels. This means that even though the reduced emissions from the transportation and industrial sectors did lead to improvements in air quality, the concentrations of some pollutants were still at unhealthy levels.

The transportation sector is not generally thought to be the major source for $PM_{2.5}$ during winters in northern China (Huang et al., 2014; Elser et al., 2016). Rather, this source has been shown to contribute to 6%–22% of the $PM_{2.5}$ mass concentration (Tao et al., 2017) and 5%–21% of the organic aerosol mass (Wang et al., 2019). The total number of motor vehicles in China increased from 5.5 million in 1990 to 327 million in 2019 (Wu et al., 2017; MPSC, 2019), which is a 60-fold increase over 30 years. However, increasingly stringent emission standards, electric vehicle subsidies, and the promotion and development of the public transportation have limited the impacts from mobile emissions (Wu et al., 2017). In fact, those measures have prevented increases in the vehicular emissions of air pollutants (except for NO_x) since 2010 (Wu et al., 2017). As a result, the contribution of the transportation sector to air pollution has not increased in parallel with the rising numbers of vehicles on the roads (Van et al., 2017).

Industrial emissions are the major contributor to $PM_{2.5}$ pollution in China (Shi et al., 2017), but the reduced emissions from that sector did not prevent air pollution during the control period. In fact, essential industries, some of which emit large amounts of pollutants, did not curtail operations during the control period for Covid-19 (MEP, 2020). For perspective, under normal circumstances, thermal power generation contributes 20.1% of the total SO_2 emissions and 32.6% of the total NO_x in China (Huang et al., 2017). These critical industries must operate continuously (Huang et al., 2017; MEP, 2020), and therefore, reducing their impacts on air quality obviously should be a central element of pollution control efforts.

The residential sector contributed 39% of the total $PM_{2.5}$ emissions in China in 2010 (Li et al., 2017), and emissions from residences were the most likely cause for air pollution during the Covid-19 control period. The industrial sector was largest contributor to fine PM in 2013 (Shi

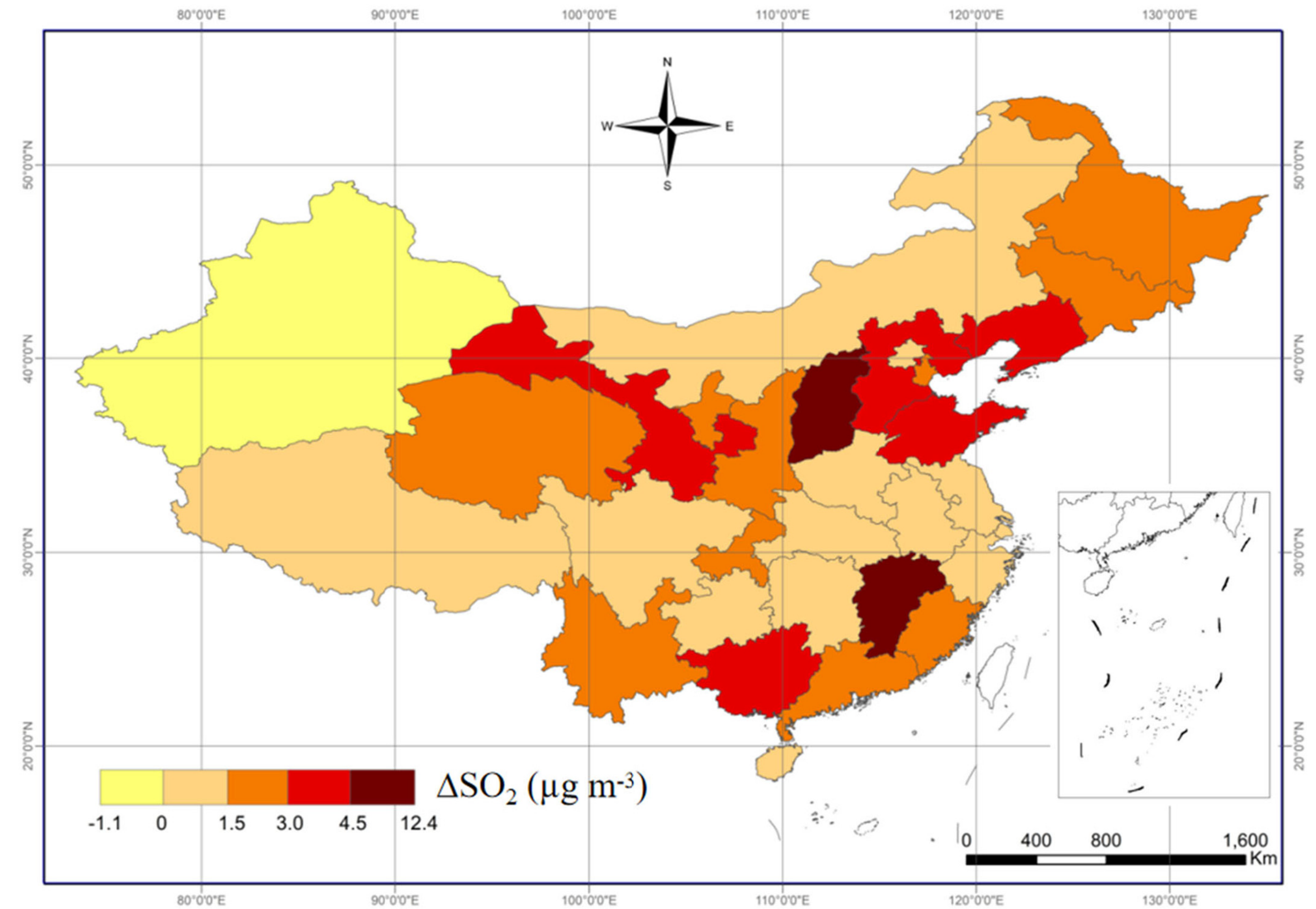

Fig. 4. Changes in the concentrations of SO_2 (ΔSO_2) during the control period for Covid-19. ΔSO_2 refers to the average SO_2 mass concentrations before the control of Covid-19 in each province minus the average SO_2 mass concentrations during the control period.

et al., 2017), but the emissions from this source decreased from 2013 to 2017 (Zhang et al., 2019), which caused the relative importance of the other pollution sources to increase proportionately. Indeed, the residential sector became the major contributor (>50%) to $PM_{2.5}$ in representative cities of northwestern China during the winter of 2016–2017 (Yang et al., 2020). Therefore, plans for controlling emissions from residences should be developed and implemented to combat air pollution during the winter in northern China.

3.3.2. Ozone pollution control

Although the reduced emissions from transportation and secondary industrial sectors did not eliminate all air pollution, NO_2, a precursor for

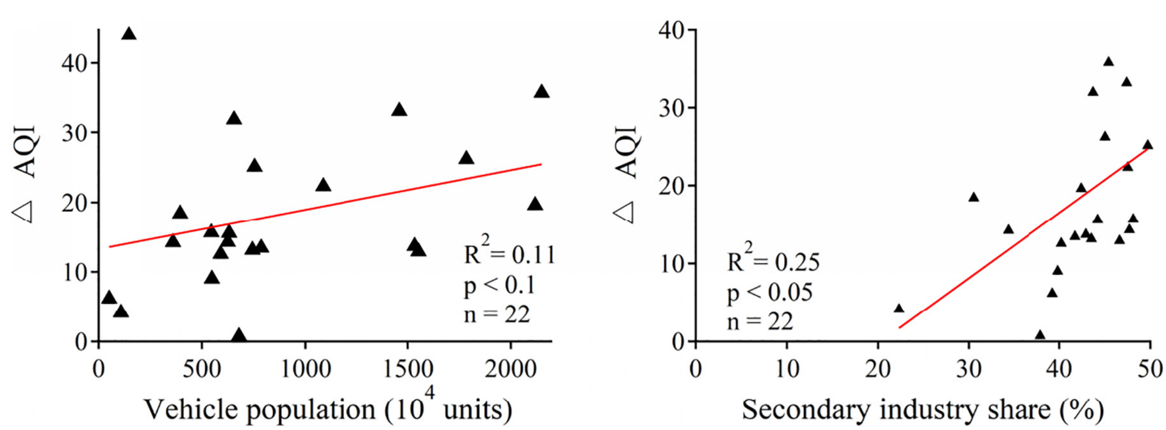

Fig. 5. Scatterplot of the change in air quality index (ΔAQI) and socioeconomic factors (number of motor vehicles, secondary industry share) in provinces with air quality improvements. ΔAQI on the Y-axis refers to the average AQI before the control of Covid-19 in each province minus the average AQI during the control period.

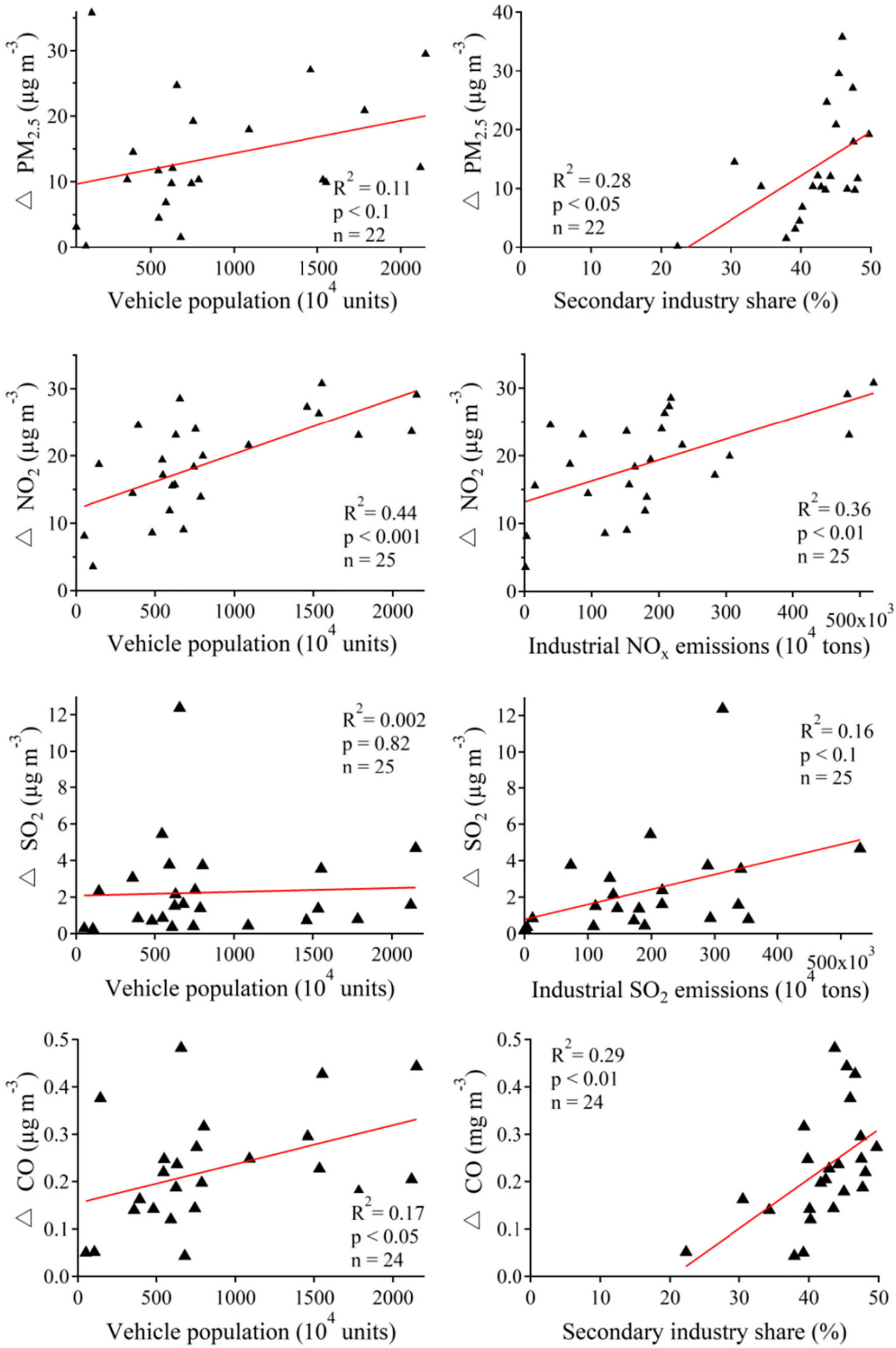

Fig. 6. Concentrations of the changes in pollutant gases ($\Delta PM_{2.5}$, ΔNO_2, ΔSO_2 and ΔCO) during the Covid-19 control period versus socioeconomic factors (vehicle population, industrial NO_x emissions, industrial SO_2 emissions, secondary industry share). The mass concentrations of pollutant gases ($\Delta PM_{2.5}$, ΔNO_2, ΔSO_2 and ΔCO) on the Y-axis refer to the average mass concentrations before the control of Covid-19 in each province minus the average mass concentrations during the control period.

O_3, did decrease dramatically during the control period (Figs. 3, S3). The emission factors for NO_x from the transportation and industrial sectors are much higher than those for other sectors (Li et al., 2017), making these the major contributors to NO_x in China (Van et al., 2017). In fact, the Multi-resolution Emission Inventory for China (MEIC) (http://www.meicmodel.org/) indicated that 64% of the NO_2 emissions originated from these two sectors.

In the troposphere, NO_x reacts with volatile organic compounds (VOCs) to form O_3, and therefore, one would expect that O_3 would have decreased along with NO_x during the control period for Covid-19; however, this was not the case. In fact, O_3 averaged over all stations increased by 20.1 μg m^{-3} from 39.0 μg m^{-3} to 59.1 μg m^{-3} (Fig. S3), and the AVC for the O_3 concentration was +51% (Fig. S3). For perspective, NO_x concentrations have been declining in China since 2011 (De Smedt et al., 2015), while O_3 has increased over the same time period (Li et al., 2019).

The observed increases in O_3 during the Covid-19 controls may be related to the observed decreases in fine particles. That is, the lower $PM_{2.5}$ would be a less effective sink for hydroperoxy radicals (HO_2), which would increase peroxy radical-mediated O_3 production (Li et al., 2019). In addition, decreased NO_x would have little or no effect on O_3 in any urban areas where O_3 production is VOC limited (Jin et al., 2015; Wang et al., 2017; He et al., 2019; Lyu et al., 2019). Simultaneously reducing both NO_x and VOC_s would be the most effective way to reduce surface ozone in China (Li et al., 2019), but the sources for VOC_s during winters in China are complex (H. Zheng et al., 2018; B. Zheng et al., 2018; Song et al., 2019; Huang et al., 2020). Indeed, controlling the NO_x emissions from transportation and secondary industries may not reduce VOC concentrations to the extent that O_3 is greatly affected.

4. Conclusions

The conclusions for the study can be summarized as answers to the questions posed in the introduction:

Did the air quality improve during the control period for Covid-19? Yes, the overall air quality improved: the AQI decreased from 89.6 prior to the control period to 71.6 during the control period. In fact, a large majority (322 of 366) of the cities studied experienced a decline in the AQI. The concentrations of five air pollutants ($PM_{2.5}$, PM_{10}, CO, SO_2, NO_2) decreased during the control period for Covid-19, but O_3 did not decrease.

Which emission sources were responsible for the reduced concentrations of atmospheric species during the Covid-19 control period? Lower emissions from motor vehicles and secondary industries most likely were responsible for the observed decreases in $PM_{2.5}$, NO_2, and CO concentrations during the control period. Lower emissions from the transportation sector were the main cause for NO_2 reduction, while the industrial sector was responsible for the $PM_{2.5}$ and CO reductions. The reduction in SO_2 was only related to reduced emissions from the industrial sector.

What are the policy implications? Despite restrictions placed on motor vehicles and secondary industries during the control period, air pollution continued to be problematic in large parts of northern China. The concentrations of O_3 actually increased during the control period, possibly because lower fine particle loadings led to less scavenging of HO_2 and as a result greater O_3 production. These results illustrate the importance of reactions that can occur between gaseous and particulate pollutants, but clearly, lowering the emissions of both NO_x and VOC_s will be needed to control O_3. Results of our study highlight the importance of emissions from the residential sector for wintertime pollution in northern China, and they show that this source must be taken into account in developing pollution mitigation plans.

CRediT authorship contribution statement

Yichen Wang: Conceptualization, Methodology, Writing - original draft. **Yuan Yuan:** Formal analysis. **Qiyuan Wang:** Writing - review & editing. **ChenGuang Liu:** Writing - review & editing. **Qiang Zhi:** Writing - review & editing. **Junji Cao:** Conceptualization, Writing - review & editing.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2020.139133.

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